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FERDINAND BRAUN – A PIONEER IN WIRELESS TECHNOLOGY AND ELECTRONICS

Peter Russer

In 1909 Ferdinand Braun and Guglielmo Marconi jointly received the Nobel Prize for their groundbreaking contributions to wireless telegraphy. Beyond numerous important contributions to wireless transmitter and receiver circuit technology Ferdinand Braun has given other epoch-making contributions to electronics and wireless technology, including the discovery of the rectifying properties of a metal-semiconductor junction in 1874, the invention of the cathode ray tube (Braunsche Röhre) in 1897, and precise voltage measurement instruments. He has given the impact to the foundation of "Hartmann & Braun" and "Telefunken" and had a considerable influence on the industrial development of German wireless technology.

Introduction

Ferdinand Braun (1850-1918) has been an extraordinary influential pioneer in wireless technology who has had a strong impact on the industrial development of that field. He has given three seminal contributions to radio science and electronics:

- The discovery of unipolar conduction of metalsemiconductor junctions in 1874 is the starting point from which solid state electronics develops.[1]
- The invention of the cathode ray tube (Braun's tube) in 1897 provided for a century the primary electronic display device for measurement equipment, radar, television and computers.[2]
- The introduction of coupled resonant circuits in wireless transmitters in 1898 allowed to bridge higher distances in wireless telegraphy and has been the precondition for Guglielmo Marconi's success in the first transatlantic wireless transmission in 1901.[3]

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1 F. Braun, "Ueber die Stromleitung durch Schwefelmetalle", *Annalen der Physik und Chemie*, 229(1875), 12, pp. 556-563, .

2 F. Braun, "Ueber ein Verfahren zur Demonstration und zum Studium des zeitlichen Verlaufes variabler Ströme", *Annalen der Physik und Chemie*, 296(1897), 3, pp. 552-559.

3 F. Braun, *Drahtlose Telegraphie durch Wasser und Luft* (Leipzig, 1901), K.F. Braun, "Electrical oscillations and wireless telegraphy", in: *From Nobel Lectures, Physics 1901-1921* (Amsterdam, 1967), pp. 226-245.

For the third contribution Ferdinand Braun together with Guglielmo Marconi received the Nobel Prize in 1909. Giving the initial impulse for the foundation of companies like Hartmann & Braun and Telefunken, Ferdinand Braun has influenced strongly the industrial development of wireless technology in Germany at the beginning of the 20th century. It has been the achievement of Friedrich Kurylo, having written the first biography of Ferdinand Braun.[4] As a reference the later biography of Florian Hars is more reliable.[5] Interesting material also can be found in[6] and in Georg Schmucker's biography of Jonathan Zenneck.[7]

Early life and education

Karl Ferdinand Braun was born on 6 June 1850 at Fulda in the Kurfürstentum [electorate princedom] Hessen as the fourth child of Johann Conrad and Franziska Braun. His father Johann Conrad Braun has been actuary at the district court Fulda. In his teens he attended the Gymnasium [high school] in Fulda, and after completing the Gymnasium he enrolled in courses in mathematics and chemistry at the University Marburg. After two semesters he moved to Berlin where he focused on Physics.[8] Professor Georg Hermann Quincke gave him an assistantship at the Gewerbeakademie Charlottenburg. He worked on his PhD under Quincke's supervision and received his doctor's degree in March 1872 with a thesis on the *oscillations of elastic strings* from the University Berlin, where Hermann von Helmholtz has been his examiner.

The birth of semiconductor electronics

In early 1872, when Georg Quincke was appointed as Professor at the University Würzburg, Ferdinand Braun followed him there as an assistant. In Würzburg the research activities of Ferdinand Braun mainly were focused on problems of electric conductivity. In the first

4 F. Kurylo, *Ferdinand Braun* (Moos, 1965).
5 F. Hars, *Ferdinand Braun (1850-1918). Ein wilhelminischer Physiker* (Berlin, 1999).
6 G. Wolfschmidt, *Von Hertz zum Handy – Entwicklung der Kommunikation* (Norderstedt, 2007).
7 G. Schmucker, "Jonathan Zenneck: 1871-1959; eine technischwissenschaftliche Biographie", Ph.D. dissertation, University of Stuttgart, 1999.
8 Hars, *Ferdinand Braun (1850-1918).*

of these works he investigated the conductivity of melted salts[9] and a second paper dealt with the unipolar electric conduction through gas layers of variable conductivity.[10] Ferdinand Braun's interest in electrical conductivity of metal salts led him to the investigation of copper sulfide crystals. In the paper with the title "Ueber die Stromleitung durch Schwefelmetalle" [About the conduction of current through metal sulfides], submitted to *Annalen der Physik und Chemie* on 23 November 1874, he reported the observation that the electrical resistance of various natural and synthetic metal sulfide samples was dependent on direction, intensity and duration of the electrical current. The disparity of the currents has been up to 30 percent.[11] He also observed, that in one direction the electrical resistance increased with decreasing current intensity and that the effect was depending on how the metallic contacts were applied to the metal sulfide sample. These effects could not be explained on the basis of existing theories. Performing his experiments accurately and repeatedly he could foreclose any error in measurement.

After working two years with Quincke, he accepted in fall 1874 a safe and well-paid teaching appointment to the St. Thomas Gymnasium in Leipzig. However, also during his engagement as a Gymnasium teacher he tried to continue his scientific work.

In the following, several researchers investigated the unipolar conductivity under different conditions and with other materials and got similar results. Werner Siemens obtained similar results with selenium if both electrodes applied to the crystal differed considerably in size.[12] Other researchers could not find unipolar conduction. Braun reacted on this with a paper about the deviations from Ohm's law in solids with metallic conductivity.[13] In this paper he concluded

> *In general the anomalous effects occur in the easiest way if at least one electrode is small. Therefore in the majority of cases I have used as the one electrode a wire which has been pressed by a spiral spring enclosed in a bushing against the crystal.*

9 F. Braun, "Ueber die galvanische Leitungsfähigkeit geschmolzener Salze", *Annalen der Physik*, 230(1875), 2, pp. 161-196.

10 F. Braun, "Ueber die unipolare Elektricitätsleitung durch Gasschichten von verschiedener Leitungsfahigkeit", *Annalen der Physik und Chemie*, 230(1875), 4.

11 Braun, "Ueber die Stromleitung durch Schwefelmetalle".

12 W. Siemens, "Ueber die Abhängigkeit der electrischen Leitungsfähigkeit des Selens von Wärme und Licht", *Annalen der Physik*, vol. 238, no. 12, pp. 521–550, 1877.

13 F. Braun, "Ueber Abweichungen vom Ohm'schen Gesetz in metallisch leitenden Körpern", *Annalen der Physik*, 237(1877), 5, pp. 95-110.

Depending on the steadiness of the material a pressure of up to one kilo has been applied. In other experiments a mercury contact has been chosen. In further experiments the crystal surface has been covered galvanoplastically with a thin copper layer and this has been overlayed with mercury. The effects are mostly, if not always, determined by the junction region. At this place a very considerable current dependent resistance is localized.

Thus Ferdinand Braun has discovered the point contact rectifier effect and by this way created the whisker diode. In[14] Ferdinand Braun reported experimental investigations of unipolar conduction on psilomelane, a hard black manganese oxide. For his experiments he used psilomelane plates mounted in a screw clamp, isolated from the clamp, so that only the peak of the clamp exhibited electrical contact to the psilomelane plate.

At this time unipolar conductivity has had no technical application, and also the physical laws governing this effect have not been known for the next fifty years. However, with his experiments performed with copper sulfide and other materials Ferdinand Braun has been the first one who has reported rectifying action of a semiconductor barrier. Ferdinand Braun's work marks the beginning of solid state electronics.[15] He never has applied this effect to realize any device and he never has claimed this, but he has opened a new branch of science, which yielded the first sensitive radio wave detectors twenty years later and today's semiconductor electronics.

The first one who has constructed and applied a semiconductor rectifier for the detection of electromagnetic waves has been Jagadis Chandra Bose, Professor of physics at the Presidency College in Kolkata, India. He used galena (lead sulfide) crystals contacted by a metal wire to detect millimeter waves. He reported this invention in the April 27, 1899, meeting of the Royal Society, London,[16] and filed 1901 a U.S

14 F. Braun, "Ueber unipolare Electricitätsleitung", *Annalen der Physik und Chemie*, 240(1878), 8, pp. 476-484.

15 E.H. Rhoderick, "The physics of Schottky barriers", *Journal of Physics D. Applied Physics*, 3(1970), 8, pp. 1153-1167; S.T. Pantelides, "The electronic structure of impurities and other point defects in semiconductors", *Reviews of Modern Physics*, 50(1978), 4, p. 797; G.I. Haddad and R.J. Trew, "Microwave solid-state active devices", *Microwave Theory and Techniques, IEEE Transactions on*, 50(2002), 3, pp. 760-779; H.B. Rockman, *Intellectual Property Law for Engineers and Scientists* (New York, 2004); R.J. Trew, "High-frequency solid-state electronic devices", *Electron Devices, IEEE Transactions on*, 52(2005), 5, pp. 638-649, .

16 J.C. Bose, "On a self-recovering coherer and the study of the cohering action of different metals", *Proceedings of the Royal Society of London*, (1899), pp. 166–172; P.K. Bondyopadhyay, "Under the glare of a thousand suns – the pioneering works of Sir J.C. Bose", *Proceedings of the IEEE*, 86(1998), 1, pp. 218-224.

patent for the point-contact semiconductor rectifier for detecting radio signals.[17] Bose's detector has been used in Marconi's first transatlantic radio transmission.[18]

In the following other inventors have realized detectors with alternative materials. On August 20, 1906, Greenleaf W. Pickard filed a U.S. patent for a silicon point contact wireless detector.[19] Henry Dunwoody filed a U.S. patent for a silicon carbide detector on March 23, 1906.[20]

It took more than fifty years after Braun's discovery until in 1928 the works of Arnold Sommerfeld[21] and Felix Bloch[22] provided an understanding of the properties of solids on the basis of quantum mechanics. Finally, upon this basis Walter Schottky presented a semiconductor theory of the junction and peak rectifiers in 1939.[23]

In his Nobel Lecture from 11 December 1909 Ferdinand Braun said:

> *In still another place, wireless telegraphy brought me into contact with earlier investigations which I had made, this time in connection with work in my youth. I found in 1874 that materials such as galena, pyrite, pyrolusite, tetrahedrite, etc., departed from Ohm's law, particularly when an electrode made contact over a small surface area. These materials greatly interested me since they conduct without electrolysis although they are binary compounds. The resistance appeared to be dependent upon the direction and intensity of the current and I could, for instance, separate the opening and closing currents of a small inductor by means of such materials, in a similar way to that of a Geisler's tube. I did not succeed in finding an "explanation" for the phenomena, for instance to what material unsymmetry the electrical unsymmetries (which without doubt existed) corre-*

17 J.C. Bose, "Detector for electrical disturbances", US Patent Nr. 755840, Application filed Sept. 30, 1901, March 1904.

18 P. Bondyopadhyay, "Sir J.C. Bose diode detector received Marconi's first transatlantic wireless signal of December 1901 (the "Italian navy coherer" scandal revisited)", *Proceedings of the IEEE*, 86(1998), 1, pp. 259-285.

19 G.W. Pickard, "Means for receiving intelligence communicated by electric waves", US Patent Nr. 836531, Application filed Aug. 20, 1906, November 1906; J. Brittain, "Electrical engineering hall of fame: Greenleaf W. Pickard", *Proceedings of the IEEE*, 93(2005), 9, pp. 1679-1681, September.

20 H.H.C. Dunwoody, "Wireless telegraphy system", US Patent 837,616, Application filed March 23, 1906, December 1906.

21 A. Sommerfeld, "Zur Elektronentheorie der Metalle", *Naturwissenschaften*, 16(1928), 21, pp. 374–381.

22 F. Bloch, "Über die Quantenmechanik der Elektronen in Kristallgittern", *Zeitschrift für Physik*, 52(1929), 7, pp. 555-600.

23 W. Schottky, "Zur Halbleitertheorie der Sperrschicht- und Spitzengleichrichter", *Zeitschrift für Physik*, 113(1939), 5, pp. 367-414; K.C. Handel, "Anfänge der Halbleiterforschung und -entwicklung", Ph.D. Dissertation, Rheinisch-Westfälische Technische Hochschule Aachen, June 1999.

sponded. I had to content myself with showing that the observed phenomena were not brought about through secondary effects such as heating. I was able to demonstrate that it appeared – at least qualitatively – even in 1/500 second, and I was convinced that – perhaps at the furthest limits – an inertialess process was concerned,…

Ferdinand Braun as an educator

Let us go back to the year 1874 when Ferdinand Braun has moved as a Gymnasium teacher to Leipzig, where he has been striving for stronger emphasis of mathematics and natural science in high-school education. In this time he wrote the book *The young Mathematician and Natural Scientist – An Introduction into the Secrets of the Number and the Miracles of Numeration*.[24] The aim of this book was to stimulate young people in mathematical thinking. In twenty-five chapters narrating evening conversations and entertainments of young people he introduces the young readers to mathematical principles governing physics, crystallography and biology. The chapters follow the course of the year. A summer thunderstorm in August gives rise to the discussion of electricity and sound. He applies combinatorics to early semaphore based communications technology. Starting with Achilles and the turtle he explains infinite series. He demands from his readers to undertake the effort solving the problems using pencil, paper, circle and ruler. He describes experiments, which the reader can perform easily.

Ferdinand Braun explains to the reader the difference between mathematics and natural science. For numbers we can find the true laws since numbers we have created with our mind, and therefore we know their meaning. In contrast to this the nature encounters the scientist as something extrinsic and it happens over and over again that we are taking an apparent rule as a law. Laws of nature have not to be considered as properties of nature but are achievements of the human mind facilitating the description of processes in nature.

This book, written for young people, also is a credo of Ferdinand Braun's scientific ethics. A reprint of the book, containing only sixteen chapters appeared in 1999.[25]

24 F. Braun, *Der junge Mathematiker und Naturforscher. Einführung in die Geheimnisse der Zahl und Wunder der Rechenkunst* (Verlag Otto Spamer, 1876).
25 K.F. Braun, *Geheimnisse der Zahl und Wunder der Rechenkunst* (Reinbek bei Hamburg, 1999).

Persons, locations and areas

In 1877 Ferdinand Braun was appointed Extraordinary Professor of Theoretical Physics at the University of Marburg. At this time Theoretical Physics has been considered subsidiary to General Physics and the positions exhibited only minor endowment. His chances for own experimental work have been quite limited and when he received in 1879 a call from the University Straßburg as the follower of Wilhem Conrad Röntgen, he accepted with pleasure and moved there in summer term 1880. Here he has had excellent working conditions and could qualify for the first appointment as Ordinary Professor which he obtained in 1883 at the Polytechnic School in Karlsruhe. Here he also became head of an own institute. From there he moved in 1885 to the University Tübingen. Soon after his arrival in Tübingen he married Amélie Bühler and in the following years four children Siegfried, Hildegard, Konrad Ferdinand, and Erika Maria were born. Figure 1 shows the photograph of Ferdinand Braun with his signature.

Figure 1. Photography of Ferdinand Braun with his signature (Photo: Deutsches Museum, Munich).

In these years Ferdinand Braun gave numerous excellent contributions to physics. One interesting development has been Braun's electrometer.[26] The University mechanic Albrecht fabricated the elec-

26 Hars, *Ferdinand Braun (1850-1918)*.

trometer designed by Ferdinand Braun in three versions with different calibrations up to 10,000 V. Ferdinand Braun's considerable demand for precise equipment at his institute in Tübingen brought him in contact with Eugen Hartmann.

Motivated by the physics Professor Friedrich Kohlrausch from the University Würzburg who needed assistance in construction of precise physical measurement equipment, in 1879, the young mechanic and former assistant of Wilhelm Weber, Eugen Hartmann founded a physical workshop.[27] Hartmann has been quite successful with his enterprise but he was lacking the funds for further expansion. When Ferdinand Braun's eldest brother Wunibald, a businessman who has spent some successful years in St. Petersburg returned to Germany, Ferdinand brought him into contact with Eugen Hartmann, and both founded in 1882 the company "E. Hartmann & Co, Würzburg" which later became "Hartmann & Braun", a world famous manufacturer of precise electrical measurement equipment. Hartmann and Braun lasted for nearly 120 years. In 1999 it has been completely integrated into the Asea Brown Boveri (ABB) group.

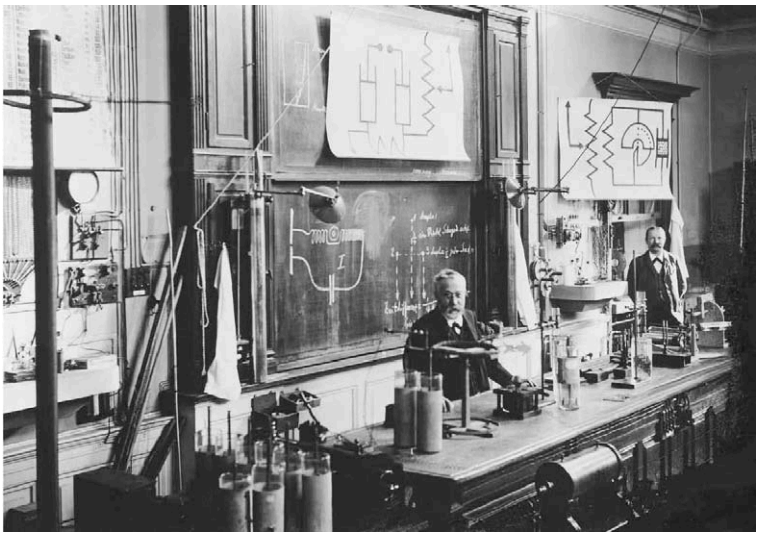

Figure 2. Ferdinand Braun in the auditorium of the Physikalische Institut of the Universität Straßburg (Photo: Deutsches Museum, Munich).

In 1895 Ferdinand Braun returned to Straßburg, where he remained, now as an Ordinary Professor and Head of the Physikalische

27 U. Haehnle, *Hartmann & Braun* (Neustetten, 2005).

Institut. Figure 2 shows Ferdinand Braun in his later years, giving an experimental physics presentation in the auditorium of the Physikalische Institut of the Universität Straßburg, and Figure 3 shows him together with assistants and students, around 1910.

Figure 3. Ferdinand Braun together with assistants and students, around 1910 (Photo: Deutsches Museum, Munich).

Braun's tube

On New Year's Day 1896 Ferdinand Braun has read Wilhelm Conrad Röntgen's publication *Über eine neue Art von Strahlen* just published on 28 December 1895.[28] On 8 November 1895, Röntgen had discovered in the Physikalische Institut of the Universität Würzburg a new kind of rays, which he called *X-rays*, and for which he should be awarded the very first Nobel Prize in Physics in 1901.[29] These invisible rays had the property to go through matter and could be visualized via a fluorescent screen or a photographic plate. When Ferdinand Braun gave this manuscript to his assistant Jonathan Zenneck to read he com-

28 W.C. Röntgen, "Über eine neue Art von Strahlen (Vorlaüfige Mitteilung)", *Sitzungsberichte der Würzburger Physik.-Medic. Gesellschaft* (1895).

29 Röntgen, "Über eine neue Art von Strahlen (Vorläufige Mitteilung)"; W.C. Röntgen, "Über eine neue Art von Strahlen (2. Mitteilung)", *Sitzungsberichte der Würzburger Physik.-Medic.-Gesellschaft* (1896); W.C. Röntgen, "Ueber eine neue Art von Strahlen", *Annalen der Physik*, 300(1898), 1, pp. 12-17; W. Petzold, "Zur Entdeckung der Röntgenstrahlen vor 90 Jahren", *Physik in unserer Zeit*, 16(1985), 6, pp. 191-193.

mented "Röntgen always has been a sane man and we not yet have shrovetide".[30] Now Ferdinand Braun's attention was attracted by the area of X-rays and cathode rays.

Ferdinand Braun's second epoch-making invention has been the cathode ray tube, also called *Braunsche Röhre* (Braun's tube).[31] In a single short paper published in Annalen der Physik on 15 February 1897, entitled "Ueber ein Verfahren zur Demonstration und zum Studium des zeitlichen Verlaufes variabler Ströme" [About a method for demonstration and investigation of the time dependence of time-variable currents] Ferdinand Braun not only described design and realization of his tube but also presented its application as an oscilloscope.[32] To fully assess the achievement of Ferdinand Braun we have to keep in mind that cathode rays in vacuum have been discovered by William Crookes one year before[33] and the existence of the electron was not known at this time. J.J. Thomson has announced his discovery of the electron during the course of his evening lecture to the Royal Institution on Friday, April 30, 1897.[34]

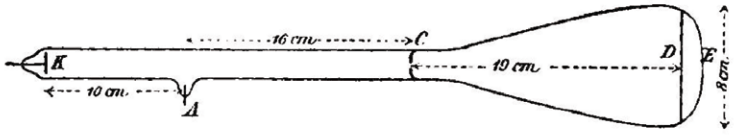

Figure 4. Schematic drawing of Braun's tube[35].

Figure 4 shows the schematic drawing of Braun's tube presented in his publication.[36] In the first paragraph of his paper Ferdinand Braun gives the following description:

30 Schmucker, "Jonathan Zenneck: 1871-1959".
31 Braun, "Ueber ein Verfahren zur Demonstration und zum Studium des zeitlichen Verlaufes variabler Ströme"; J.J. Peters, "A history of television", *European Broadcasting Union* (2000); M. Thumm, "Historical German contributions to physics and applications of electromagnetic oscillations and waves", in *Proc. Int. Conf. on Progress in Nonlinear Science, Nizhny Novgorod, Russia*, 2(2001), pp. 623-643; M. Thumm, "Historical German contributions to physics and applications oscillations and waves", in: T. K. Sarkar, R. Mailloux, and A. A. Oliner eds., *History of Wireless* (New York, 2006), pp. 327-348.
32 Braun, "Ueber ein Verfahren zur Demonstration und zum Studium des zeitlichen Verlaufes variabler Ströme".
33 C.N. Hinshelwood "William Crookes", University of Oxford, Department of Chemistry, Website. http://www.chem.ox.ac.uk/icl/heyes/ LanthAct/Biogs/Crookes.html.
34 J.J. Thomson, "On cathode rays", *Phil. Mag.*, s. 5, 44(1897), 8, p. 293; J.J. Thomson, "Carriers of negative electricity", in: *From Nobel Lectures, Physics 1901-1921* (Amsterdam, 1967).
35 Braun, "Ueber ein Verfahren zur Demonstration und zum Studium des zeitlichen Verlaufes variabler Ströme".
36 Braun, "Ueber ein Verfahren zur Demonstration und zum Studium des zeitlichen Verlaufes variabler Ströme".

The method described in the following utilizes the deflectability of cathode rays by magnetic forces. These rays have been produced in tubes, from one of which I will specify the dimension, since these ones seem to me to be in general the most advantageous ones (Figure 5). K is the aluminium cathode, A the anode, C an aluminium diaphragm with a hole of 2 mm diameter. D is a mica screen covered with phosphorescent dye. The glass well E must be applied as uniform as possible, so that the fluorescent spot effected by the cathode ray can be seen.

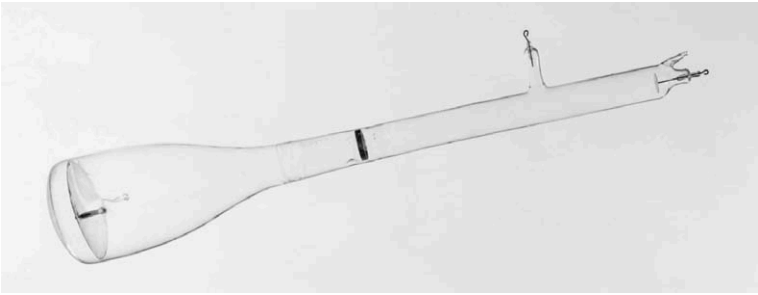

Figure 5. The Braun's tube (Photo: Deutsches Museum, Munich).

Ferdinand Braun mentions that Franz Müller, the successor of Heinrich Geißler in the workshop for physical instruments founded by Geißler in Bonn has fabricated the tube in established excellent quality. Figure 5 shows the photograph of an original Braun's tube.

The high voltage required for the experiments has been generated with a Toepler influence machine. For the deflection of the cathode ray Ferdinand Braun applied a magnetic field generated by a magnetization coil positioned close to the diaphragm and with axis perpendicular to the axis of the tube. This coil he called "indicator coil". To observe the time dependence of time-variable currents he deflected the cathode ray with a single coil and observed the screen via a rotating mirror. Although he has shown in the same paper also two-dimensional deflection using two perpendicular indicator coils, he used the rotating mirror solution since a linear ramp generator has not been available at this time. Figure 6a shows the sinusoidal time dependence of a 50 Hz ac current from the grid of the Straßburg power station in comparison with the sinusoidal oscillation of a tuning fork depicted in Figure 6b. The curves were sketched by hand according to their appearance in the rotating mirror.

Figure 6. Measured waveforms of the time dependence of (a) ac current of the Straßburg power station, (b) tuning fork oscillation[37].

Figure 7 shows the time dependence of the current through the primary coil of an induction coil. For open secondary coil (case a), the rise α-β of the current occurs such fast that this part of the curve is difficult to realize. During the interval β-γ the spark at break still gives contact.

With an arrangement of two perpendicular indicator coils Ferdinand Braun also has demonstrated two-dimensional deflection of the cathode ray. He supplied both indicator coils with currents flowing through the primary and secondary of a Ruhmkorff coil with fixed interruptor. By inserting inductors without and with iron cores and also connecting a capacitor to the circuit he could vary the phase delay between the indicator coils and also produce 3rd harmonics as can be seen from the Lissajou's figures depicted in Figure 8.

This invention also became important for his research work on wireless telegraphy. Let me cite from his Nobel Lecture from 11 December 1909:

> *…might perhaps recall an accessory which was of great use to me and other experimenters. I mean the cathode-ray tube which I described in 1897. It provided a visual picture of current- and voltage-waveforms up to 100 kc/s, and was the means by which investigations of period, waveform, intensity and thereby damping, as well as relative phases, could be made.*[38]

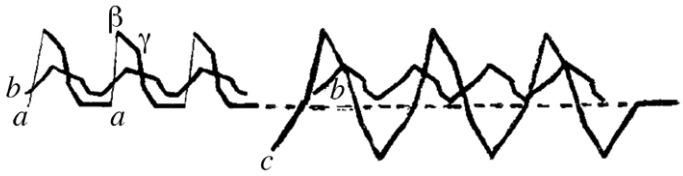

Figure 7. Measured waveforms of the time dependence oft the current through the primary coil of a Ruhmkorff induction coil for (a) secondary coil open circuited, (b) secondary circuit short-circuited, (c) secondary coil terminated with a capacitor[39].

37 Braun, "Ueber ein Verfahren zur Demonstration und zum Studium des zeitlichen Verlaufes variabler Ströme".
38 Braun, "Electrical oscillations and wireless telegraphy".
39 Braun, "Ueber ein Verfahren zur Demonstration und zum Studium des zeitlichen Verlaufes variabler Ströme".

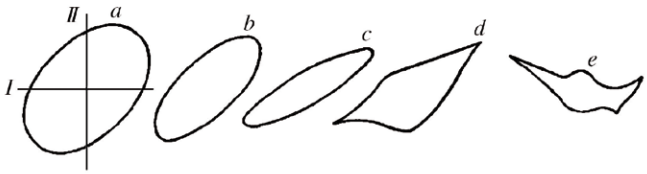

Figure 8. Measured Lissajou's figures[40].

With this cathode ray tube Ferdinand Braun also has realized the first cathode ray oscilloscope. For one century cathode ray tubes have been the dominant electronic display devices and have made possible television and radar.

Wireless telegraphy

Heinrich Hertz, who on 11 November 1886, has demonstrated generation, transmission and detection of electromagnetic waves experimentally for the first time[41] never has intended to utilize them for communications. Wireless telegraphy has been established by Guglielmo Marconi, an engaged and ambitious autodidact. He never has studied physics but has had the opportunity to attend courses of Professor Augusto Righi at the University Bologna, where he became acquainted with wireless transmission. In 1895 Guglielmo Marconi, in the age of 21, performed his first wireless transmission experiments. In the year 1897 he already could bridge a distance of 14 km between Lavernock Point and the island Flat Holme in the Bristol Channel and in 1899 he has been able to bridge the English Channel. The early history of wireless telegraphy is reviewed in.[42]

In 1897 Adolph Slaby, Professor at the Charlottenburg Technical Academy in Berlin, participated in Marconi's wireless telegraphy experiments across the English Channel. After returning to Berlin, on 7 October 1897 he succeeded in establishing a 21 kilometer wireless

40 Braun, "Ueber ein Verfahren zur Demonstration und zum Studium des zeitlichen Verlaufes variabler Ströme".

41 H. Hertz, "Ueber sehr schnelle electrische Schwingungen", *Annalen der Physik und Chemie*, 267(1887), 7, pp. 421-448, .

42 M. Thumm, "Historical German contributions to physics and applications of electromagnetic oscillations and waves"; M. Thumm, "Historical German contributions to physics and applications oscillations and waves"; I.V. Lindell, "Wireless before Marconi", in: T. K. Sarkar, R. Mailloux, and A. A. Oliner eds., *History of Wireless*, pp. 247-266; J.S. Belrose, "The development of wireless telegraphy and telephony, and pioneering attempts to achieve transatlantic wireless communications", in *History of Wireless*, pp. 349-420.

transmission between Schöneberg and Rangsdorf, which has been a world record.[43]

In 1898 Ferdinand Braun rather by chance came to wireless telegraphy. The entrepreneur Ludwig Stollwerck who has made his fortune with chocolate vending machines was going to engage in a consortium dealing with the development of wireless telegraphy and contacted Ferdinand Braun for expert advice.[44]

In his work on wireless transmission Ferdinand Braun has been assisted by Mathias Cantor and Jonathan Zenneck (Figure 9). Mathias Cantor investigated Branly's coherer,[45] the most sensitive radio wave detector device at this time, the operation of which is based on an electrical conduction instability that occurs in an oxidized metallic powder under a constraint.[46] Cantor has shown that also continuous electrical discharges through gas under low pressure can generate electromagnetic waves.[47]

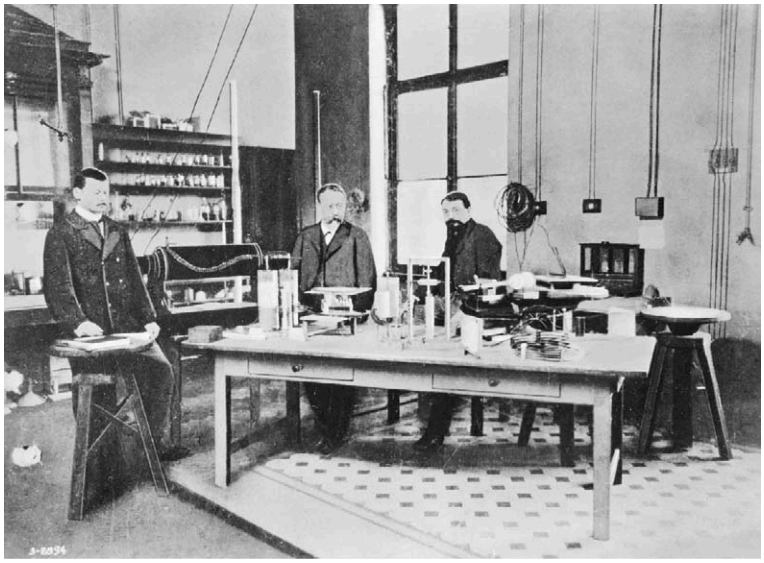

Figure 9. Jonathan Zenneck, Ferdinand Braun, and Mathias Cantor (from the left) in the laboratory of the der Universität Straßburg at 1899 (Photo: Deutsches Museum, Munich).

43 M. Salazar-Palma, T.K. Sarkar, and D.L. Sengupta, "A chronology of developments of wireless communication and supporting electronics", in: *History of Wireless*, pp. 53-164.
44 Hars, *Ferdinand Braun (1850-1918)*; G. Schmucker, "Jonathan Zenneck: 1871-1959".
45 E. Branly, "Variations de conductibilité sous diverses influences électriques", *C. R. Acad. Sci. Paris*, 111(1890), pp. 785-787.
46 E. Falcon and B. Castaing, "Electrical conductivity in granular media and Branly's coherer: A simple experiment", *American Journal of Physics*, 73(2005), 4, pp. 302–307.
47 M. Cantor, "Ueber die Entladungsform der Elektricität in verdünnter Luft", *Annalen der Physik und Chemie*, 303(1899), 2, pp. 481-484.

Braun studied the work of Lodge, Marconi and Slaby and tried to find out why both, Marconi and Slaby had difficulties to increase the distance of wireless transmission. Marconi already had performed wireless transmission over 50 km, however, this required a large transmitter power.

Figure 10a shows various arrangements of the tightly coupled primal Marconi transmitter. In all three cases the spark gap excited by a Ruhmkorff induction coil S is directly connected to antenna and ground. In Figure 10a1 the transmitter exhibits only an antenna wire. As in the Hertzian arrangement from 1886 the steep transients of the spark discharges excite eigenoscillations of the antenna wire. In Figure 10a2 a plate on the top of the antenna wire is added, providing a capacitive load. In Figure 10a3 the Hertzian spark gap is replaced by the so-called Righi oscillator, a system with three sparks, where the oscillating discharge in the center does not take place in the air. This arrangement yielded no improvement. Augusto Righi's main achievement is having motivated Guglielmo Marconi to engage himself in wireless transmission. In his paper from 1952 Jonathan Zenneck has pointed out that at the time when Marconi has made his experiments many researchers were thinking, that in the spark gap oscillations of very short wavelength in the order of centimeters are generated which than are travelling upwards through the antenna wire.[48] This makes the concept of the Righi oscillator graspable. Although we know today that the primal Marconi transmitter exhibited inherent drawbacks we have to acknowledge that with this arrangement for the first time wireless telegraphy has been realized.

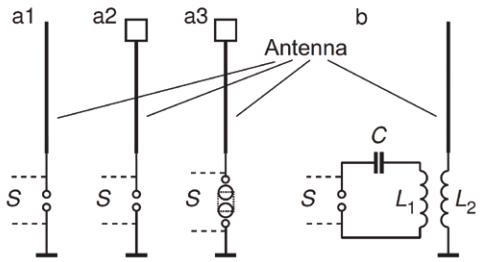

Figure 10. Spark gap transmitters: a) Primal Marconi transmitters with 1) only spark gap, 2) plate, 3) plate and Righi oscillator; b) Braun's coupled transmitter arrangement, after[49].

48 J. Zenneck, "Aus der Kindheit der drahtlosen Telegraphie", *Naturwissenschaften*, 39(1952), 18, pp. 409-418.
49 Zenneck, "Aus der Kindheit der drahtlosen Telegraphie".

The tight coupling of the antenna to the oscillator in the Marconi arrangements yielded high damping and consequently the distribution of the transmitted power over a broad frequency band and therefore interference to other stations. The power losses were high and a tuning of the transmitter was not possible.

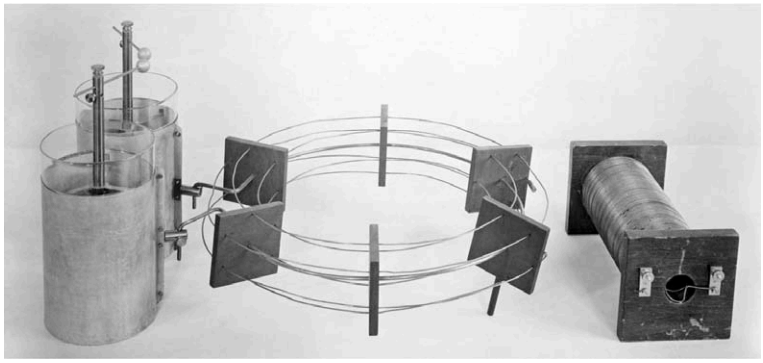

Figure 11. Closed resonant circuit with air transformer after Ferdinand Braun from year 1898 (Collection of Deutsches Museum, Munich).

Ferdinand Braun intentionally wanted to use longer wavelengths. According to B.W. Feddersen this could be achieved using capacitors.[50] Therefore Ferdinand Braun has chosen an arrangement according to Figure 10b where he could distribute the two tasks, generation of oscillation and radiation over two circuits. The loose coupling between the spark-gap oscillator and the antenna yielded lower damping, a narrower spectral width of the radiated pulses and higher power efficiency. The circuit could be tuned in frequency and using two resonant circuits further improved the efficiency. Braun patented a transceiver with coupled resonant circuits (DR Patent Nr. 111578, October 14, 1898).[51] Figure 11 shows a replica of the closed resonant circuit with air transformer after Ferdinand Braun from year 1898.[52]

50 Zenneck, "Aus der Kindheit der drahtlosen Telegraphie"; B.W. Feddersen, *Beiträge zur Kenntniss des elektrischen Funkens* (C. F. Mohr, 1857).

51 F. Braun, "Schaltungsweise des mit einer Luftleitung verbundenen Gebers für Funkentelegraphie", DR Patent Nr. 111578, October 14 1898; F. Braun, "Telegraphiersystem ohne fortlaufende Leitung", DR Patent Nr. 115081, July 12 1898; F. Braun, "Reinforcement of electrical waves and avoidance of loss by straying, reflection, and the like, by means of a condenser", GB Patent Nr. 189905104, Application filed November 3, 1899, March 8 1900.

52 Braun, "Telegraphiersystem ohne fortlaufende Leitung".

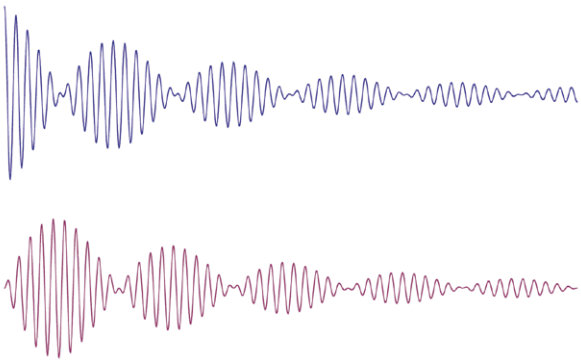

Figure 12. Time dependence of the currents in Braun's coupled transmitter – capacitor circuit (upper trace), antenna circuit (lower trace), after[53].

The time response in the primary and secondary coils of Braun's coupled transmitter are depicted in Figure 12.[54] The transient shows the superposition of two attenuated eigenoscillations according to the two resonant frequencies of the coupled system.

Ferdinand Braun has made his first transmission experiments in 1898 in Straßburg and at the Rhine where he could bridge distances of 1600 m and at the North Sea near Cuxhaven where he reached 3km.

After assignment of the patent[55] Ferdinand Braun gave a presentation about his work on wireless telegraphy at the Straßburg Society of Natural Science and Medicine on 16 November 1900,[56] and in 1901 he published his book on wireless telegraphy.[57]

In his Nobel Lecture from 11 December 1909 Ferdinand Braun has said

> *If I am to give you the general thoughts and concepts which guided me I must ask you to carry yourselves back with me to the standpoint of our knowledge at that time. What facts were at our disposal and what conclusions could be drawn from them? It was known how sensitive the Hertzian oscillations were to the quality of the spark, and also that lengthening the spark led to definitely deleterious effects whereby the spark became 'inactive'. Hertz had already, in his first work, called attention to the strong damping of the oscillators and compared their electrical oscillations with the ill-defined acoustic oscillations of wooden rods.*[58]

53 Zenneck, "Aus der Kindheit der drahtlosen Telegraphie".
54 Zenneck, "Aus der Kindheit der drahtlosen Telegraphie".
55 Braun, "Schaltungsweise des mit einer Luftleitung verbundenen Gebers für Funkentelegraphie".
56 Hars, *Ferdinand Braun (1850-1918)*.
57 Braun, *Drahtlose Telegraphie durch Wasser und Luft*.
58 Braun, "Electrical oscillations and wireless telegraphy".

Guglielmo Marconi borrowed the principle of coupled circuits from Ferdinand Braun, and in his later "7777"–patent he claimed the tuning of primary and secondary coils in transmitter and receiver as well as the tuning between transmitter and receiver.[59]

A founder of industry

For the advancement of wireless telegraphy a company with the name "Professor Braun's Telegraphie G.m.b.H." with the short name "Telebraun" was founded in May 1900 in Hamburg.[60] Besides Stollwerck and other capital providers also the Electricitäts-Actiengesellschaft, formerly Schuckert & Co. joined the consortium. Transmission experiments were continued near Cuxhaven by Mathias Cantor and Jonathan Zenneck. With components delivered by Schuckert, a distance of 62 km could be bridged in September 1900. Figure 13 shows the components of the first wireless transmission system Cuxhaven-Helgoland.

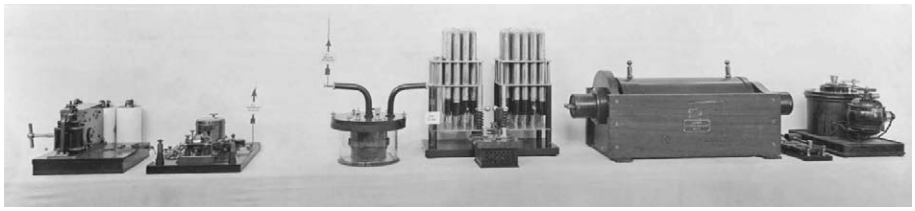

Figure 13. Components of the first wireless transmission system Cuxhaven -Helgoland (Photo: Deutsches Museum, Munich).

Schuckert has left the consortium in 1899 and now Siemens & Halske joined. On 27 July 1901 the "Gesellschaft für drahtlose Telegraphie System Prof. Braun und Siemens & Halske m.b.H." has been founded in Berlin.

In the meantime Adolph Slaby was working for AEG (Allgemeine Elektricitätsgesellschaft).[61] Siemens and AEG, the two largest German electrical engineering companies now have been in strong competition in the area of wireless telegraphy. Braun-Siemens worked for the army and AEG with Slaby and Arco primarily for the navy. Wilhelm von Siemens and Emil Rathenau, founder and general manager of AEG recog-

59 Zenneck, "Aus der Kindheit der drahtlosen Telegraphie"; G. Marconi, "Improvements in apparatus for wireless telegraphy", GB Patent Nr. 190007777, Application filed April 26, 1900, April 13 1901.
60 Hars, *Ferdinand Braun (1850-1918)*.
61 P. Strunk, *Die AEG Aufstieg und Niedergang einer Industrielegende*, (Nicolai, 2002).

nized the chances of a merger of the wireless telegraphy activities of both companies.[62] The German Emperor Wilhelm II, who exhibited lively interest in economics and technology[63] also brought his influence to bear and on 27 May 1903 S & H and AEG founded the innovative start-up company "Gesellschaft für drahtlose Telegraphie" (Company for Wireless Telegraphy), where both partners held equal share.[64] The products were marketed under the brand "System Telefunken" and on 11 November 1903 the trade mark "Telefunken" has been registered at the Imperial Patent Office in Berlin. The name "Telefunken" primarily has been a telegraphic address, already introduced by Ferdinand Braun in 1901.

The North American Years

Shortly after begin of the First World War Ferdinand Braun was summoned to New York to attend as a witness in a lawsuit regarding a patent claim of the American Marconi company against the Atlantic Communication Company, a subsidiary of Telefunken, supplying wireless telegraphy between Germany and Sayville, NY. Jonathan Zenneck, accompanied him as a Technical Advisor of the Atlantic Communication Company. In December 1914 Ferdinand Braun and Jonathan Zenneck set sail from Bergen in Norway, a demounted 125 m antenna in their luggage, taking a route far in the North to compass the British sea blockade. After success in that law suit, the operation of the Atlantic Communication Company station could be maintained until the United States entered the war on 6 April 1917. The circumstances of war made a return to Germany impossible and Ferdinand Braun lived at his son's home in Brooklyn, NY and in Summer in the Catskill Mountains. He died on 20 April 1918 in Brooklyn.[65]

Final Remarks

Despite of his seminal contributions in three important areas of technology Ferdinand Braun's achievements are little known. One reason may be that he always avoided publicity and never strove for fame and

62 E. Thiele, *Telefunken nach 100 Jahren: Das Erbe einer deutschen Weltmarke,* (Nicolai, 2003).
63 C. Clark, *Kaiser Wilhelm II.* (London-New York, 2000).
64 Thiele, *Telefunken nach 100 Jahren: Das Erbe einer deutschen Weltmarke*; *25 Jahre Telefunken: Festschrift der Telefunken Gesellschaft, 1903-1928* (Telefunken GmbH, 1928).
65 Kurylo, *Ferdinand Braun*; Hars, *Ferdinand Braun (1850-1918)*; Schmucker, "Jonathan Zenneck: 1871-1959".

personal recognition for his work. He solely served the advancement of science.

In his presentation speech made prior to the joint awarding of the 1909 Nobel Prize in Physics to Braun and Marconi, the President of the Royal Swedish Academy of Sciences H. Hildebrand has impressively summarized significance of Braun's work, saying:

> *Marconi's original system had its weak points. The electrical oscillations sent out from the transmitting station were relatively weak and consisted of wave-series following each other, of which the amplitude rapidly fell – so-called 'damped oscillations.' A result of this was that the waves had a very weak effect at the receiving station, with the further result that waves from various other transmitting stations readily interfered, thus acting disturbing at the receiving station. It is due above all to the inspired work of Professor Ferdinand Braun that this unsatisfactory state of affairs was overcome. Braun made a modification in the layout of the circuit for the dispatch of electrical waves so that it was possible to produce intense waves with very little damping. It was only through this that the so-called 'long distance telegraphy' became possible, where the oscillations from the transmitting station, as a result of resonance, could exert the maximum possible effect upon the receiving station. The further advantage was obtained that in the main only waves of the frequency used by the transmitting station were effective at the receiving station. It is only through the introduction of these improvements that the magnificent results in the use of wireless telegraphy have been attained in recent times.*[66]

Acknowledgements

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66 H. Hildebrand, "The Nobel prize in physics 1909, presentation speech", in: *From Nobel Lectures, Physics 1901-1921* (Amsterdam, 1967).

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